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Primordial light element abundances

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Abstract.

After few minutes the Universe evolved through conditions of temperature and density which permitted the first synthesis of astrophysically interesting abundances of D, ^3He , ^4He and ^7Li . The relic abundances are sensitive probes of the nucleon density and so are the CMB acoustic oscillations, somewhat 400000 years later, which allow a stringent cross check. The CMB high precision estimate of the baryon density by WMAP is currently used as input parameter for standard big bang nucleosynthesis (SBBN) to interpret primordial abundances rather than being directly derived from the observations of light elements as was common use before. New atomic physics and identification of systematics lead to an upwards revision of the ^4He primordial abundance at $Y_p=0.2477\pm0.0029$ (Peimbert et al 2007) removing a major source of tension between SBBN and WMAP. The D/H as measured in QSO high redshift absorbing clouds shows an excess of scatter but the mean value is found in spectacular agreement with the WMAP- Ω_b prediction. The Li/H recently redetermined in halo dwarfs is more than a factor 4 lower than expected. We argue that the difference reduces to a factor 2 when the IRFM Teff scale is adopted. Diffusion has been suggested to have depleted Li in halo dwarfs by the required amount to remove the gap, however this would imply an implausible high abundance of the more fragile ^6Li detected in some halo dwarfs, thus leaving the puzzle open.

1. John Beckman and the light elements

The organizers asked me to review the status of the light elements, which is one of J.E. Beckman's interests although a bit aside the main theme of this unique and enjoyable conference. John's interest on light elements dates back to the 80's at the epoch of his definitive move to IAC. The start was a search for BeII lines in HD76932 by means of IUE spectra, a star belonging to the first sample of halo stars where Francois and Monique Spite observed the primordial Li. The upper limit provided for Be showed that spallation processes of high energy cosmic rays were not an alternative to primordial nucleosynthesis to make up for all or a fraction of the Li observed in the star, thus supporting its primordial origin (Molaro & Beckman 1984). This work was followed by the first Be detections in halo stars by means of the Image Photon Counting System at the Isaac Newton Telescope on La Palma and reported in Rebolo et al (1988a). In the same years a Li observational campaign was conducted from La Palma with INT and first results presented at the second IAP workshop in Paris (Beckman et al 1986), and then in a more definitive shape in Rebolo et al (1988b). This was the first confirmation of the primordial Spite and Spite halo plateau made by and independent group, significantly enlarging the sample of halo stars in number

and physical properties, in particular with a significant extension in metallicity down to $[\text{Fe}/\text{H}]=-3.5$, which is not very far from where we are today. After these pioneering works the research of light elements became very active at the IAC where R. G. Lopez and E. Martin, among the others, extended the work to other light elements (B) and to other environments such as stellar clusters, cool x-ray-binary companions and brown dwarfs. A field still very active today at IAC.

2. The WMAP- $\Omega_b h^2$ primordial abundances

The number of baryons is set once for all at the baryogenesis and is constant in a comoving universe. When the universe was few minutes old it evolved through conditions of temperature and density which permitted the first synthesis of astrophysically interesting abundances of D, ^3He , ^4He and ^7Li . While the ^4He abundance is determined primarily by the universal expansion rate and is sensitive to the number of relativistic particles at the nucleosynthesis epoch, D and Li abundances depend strongly from the available nuclei. In the standard BB nucleosynthesis with 3 neutrino flavours the only free parameter is the relative number of baryons to photons, namely $\eta = n_b/n_\gamma$. In the range of interest $3 < 10^{10}\eta < 8$, D/H and Li/H show the strongest dependence on η and therefore on the particle density, these are $\propto \eta^{-1/6}$ and $\propto \eta^2$, respectively.

The value of the baryon density can be measured from the acoustic oscillations in the CMB since the baryonic component determines the inertia of the mass-photon fluid. The ratio of the compressible peaks of CMB power spectrum are sensitive to the baryonic density and allow a very precise measure of Ω_b . Considering the WMAP-Only 3 year data, Spergel et al (2007) derived $\Omega_b h^2 = 0.02233^{+0.00072}_{-0.00091}$.

The number of photons is also constant in a comoving universe after e^\pm annihilation and therefore $\eta = 10^{10}(n_b/n_\gamma)_0 = (273.9 \pm 0.3)\Omega_b h^2$, where the small error enters in the conversion from number to mass densities (Steigman 2006). The WMAP value for $\Omega_b h^2$ yields $\eta = 10^{10}(n_b/n_\gamma)_0 = 6.116^{+0.197}_{-0.249}$ which fixes the primordial abundances of the light elements in the framework of SBBN. By using Kneller and Steigman (2004) approximations of primordial yields in the range $3 < 10^{10}\eta < 8$ we obtain the predicted primordial abundances reported in Table 1, where the primordial ^4He , Y_p , is given in mass fraction and the other light elements in number fractions with respect to hydrogen.

Table 1. WMAP primordial abundances

Element	SBBN+WMAP
Yp	$0.2482^{+0.0004}_{-0.0003}$
$^3\text{He}/\text{H}$	$(10.5 \pm 0.6) \cdot 10^{-6}$
D/H	$(25.7^{+1.7}_{-1.3}) \cdot 10^{-6}$
Li/H	$(4.41^{+0.3}_{-0.4}) \cdot 10^{-10}$

However, some degeneracies are present in the derivation of the cosmological parameters from the CMB power spectrum. In particular $\Omega_b h^2$ depends from the index of the power law of primordial fluctuations and from the opacity at the reionization epochs. For instance, the WMAP 3 year combined with all other relevant datasets with a running spectral index is providing $\Omega_b h^2 = 0.02065^{+0.00083}_{-0.00082}$. This value gives $\eta_{10} = 5.656^{+0.227}_{-0.225}$ and the predicted primordial abundances become: $Y_p = 0.2474^{+0.0004}_{-0.0003}$, $D/H = (29.1^{+1.9}_{-1.8}) \cdot 10^{-6}$ and $Li/H = (3.8 \pm 0.4) \cdot 10^{-10}$ with about 11% shift upwards for D/H abundance and 14% downwards for Li/H. Thus, uncertainties regarding priors are a significant source of systematic errors which slightly exceed the statistical error in the prediction of $\Omega_b h^2$. Nevertheless, the CMB precision estimate of the baryon density remains high and should be used as input parameter to interpret primordial abundances rather than being directly derived from the observations of light elements as it was usual before WMAP. Only an unlikely knowledge of a primordial D or Li abundance with an accuracy greater than 10-15% could reverse the logical path.

3. Helium

Primordial helium is best determined through recombination of HeII and HII lines in extragalactic, almost chemically unevolved HII regions, with an extrapolation to zero metallicity to account for stellar production. Fig. 1 shows the behaviour of the ^4He determinations in the last decades. After many years with rather low values we have now approached the WMAP values thus removing a major source of tension between WMAP and BBN. Olive and Skillman (2004) stressed the importance of systematic errors and derived $Y_p = 0.2495 \pm 0.0092$., while Peimbert et al (2007) make a list of 13 different types of errors, several of systematic origin, entering in the primordial ^4He determinations. Fukugita and Kawasaki (2006) considered carefully the underlying ^4He stellar absorption and derived $Y_p = 0.250 \pm 0.004$. Peimbert, Luridiana & Peimbert (2007) derived $Y_p = 0.2477 \pm 0.0029$ by using the new recombination coefficients of HeI from Porter et al (2005) and excitation collisional coefficients for H from Anderson et al (2002). This new physics alone determine a 0.008 dex increment in the ^4He determination. By using the Porter et al emissivities Izotov et al (2007) obtained $Y_p = 0.2516 \pm 0.0011$ which exceed by 2σ the predicted WMAP value implying a slight deviation, but of different sign, from SBBN.

^3He has a complex post-BBN evolution with unclear stellar production. Bania, Rood and Balser (2002) after 20 years of heroic observations of the most distant Galactic HII region suggest 11 ± 2 ppm (parts-per-million) as the best upper limit on the primordial ^3He abundance, essentially derived from the observation of a single HII nebula. This is in excellent agreement with the WMAP value 10.5 ± 0.6 ppm, but considering the large uncertainties involved ^3He is not imposing strong constraints on SBBN.

4. Deuterium

Deuterium has a very simple chemical evolution history. It cannot be produced by other sources than the BBN and whenever it is cycled in stars it is entirely

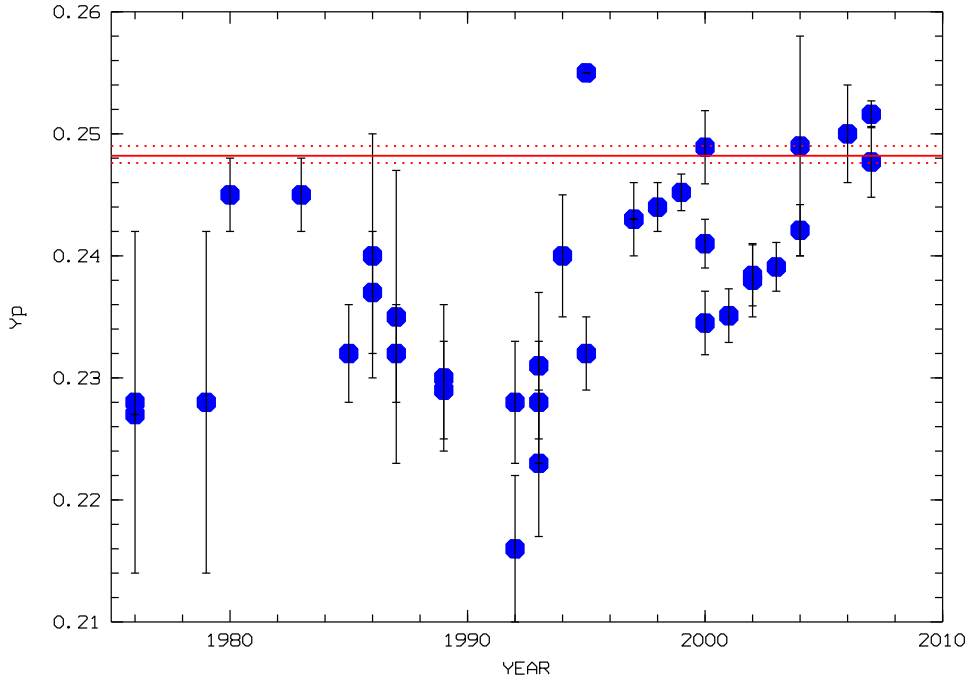


Figure 1. Historical record of ^4He determinations. The WMAP-SBBN predicted primordial value is also shown with the red line and 1σ error.

burned out. The possibility of observing primordial D/H in distant chemically unevolved clouds was predicted already by Adams (1976) but the first observations were those of Tytler et al (1996) and after a decade of 8-10 m large telescope observations we remain with only 8 measurements. The observations are shown in Fig. 2 where they are plotted with respect to the neutral hydrogen column densities which imply different types of absorbers. The sub-DLA cases with hydrogen column densities $\text{LogN}(\text{HI}) \leq 19 \text{ cm}^{-2}$ between are those which better match the WMAP value. Kirkman et al (2003) claimed for the presence of a correlation between D/H and HI, but the new measurements of O'Meara et al (2006) of $33.1 \pm 4.3 \text{ ppm}$ (parts-per-million) at $\text{LogN}(\text{HI})=20.67 \text{ cm}^{-2}$ and the one of Crighton et al (2004) $16.0 \pm 2.5 \text{ ppm}$ at $\text{logN}(\text{HI})=18.25 \text{ cm}^{-2}$ showed that the supposed correlation with HI was an artifact produced by poor statistics. The systems show low metallicities in the range $-3 < [\text{Si}/\text{H}] < -1$ and no hint of correlation between D/H and metallicity or redshift. At these metallicities no significant astration is foreseen according to Romano et al (2003) computations, and the measurements should reflect essentially pristine gas composition. From Fig. 2 it is evident that the dispersion of the measures exceeds the reported errors suggesting at face value either the presence of a scatter in the D/H or an underestimation of the errors in some or all measurements. The unweighted average of the D/H gives $28.1 \pm 9 \text{ ppm}$, with the central value in excellent agreement with the $25.7^{+1.7}_{-1.3} \text{ ppm}$ of WMAP. It is really a very unfortunate case that we do not understand the cause of the observed scatter since it prevents the potential use of D/H into the identification of the priors in the CMB analysis.

A matter of concern are the Galactic D/H abundances, which turn out to be more complex than the high redshift universe. Fuse has provided a lot of new data confirming the dispersion in the galactic disk values with a bimodal distribution of high ($\text{D}/\text{H}=23.1 \pm 2.4 \text{ ppm}$) and low values ($10.1 \pm 3.3 \text{ ppm}$) once

cleaned from the local bubble values, which cluster onto a third value (15.8 ± 2.1 ppm) (Savage et al 2007, Linsky et al 2006). The measurements show a correlation with Fe abundances suggesting a depletion of D into dust grains. A new measurement of the deuterium hyperfine transition towards the Galactic anticenter region of 21 ± 2.3 ppm is also consistent with the high D/H values in the solar neighborhood (Rogers et al 2007). The high values should therefore be more representative of the gas phase abundances but they impose tight constraints on the amount of minimum recycling foreseen in the Galactic chemical evolution and require infall of primordial D (Steigman et al 2007).

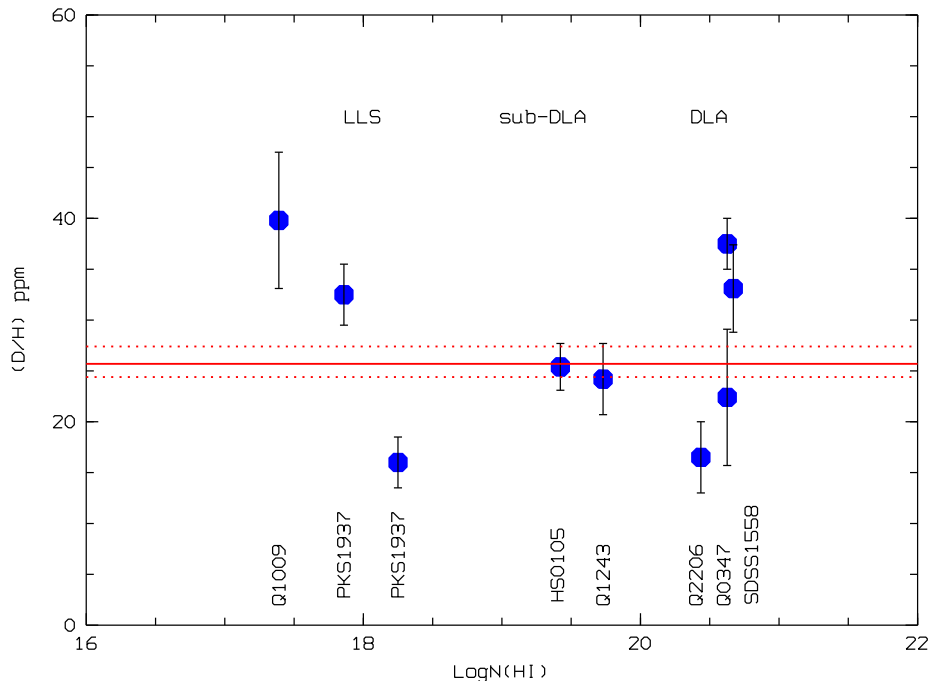


Figure 2. D/H versus hydrogen column density. The labels identify the QSO where the D/H has been measured: Q1009+299 is from Tytler et al (1996), PKS1937-1009 are from Burles and Tytler (1998) and from Crighton et al (2004), HS0105 +1619 is from O’Meara et al (2001); Q1243+3047 is from Kirkman et al (2003), Q2206-199 is from Pettini and Bowen (2001); for Q0347-383 there are two determinations of the same system by D’Odorico et al (2001) and by Levshakov et al (2002); SDSS1558-0031 is from O’Meara et al (2006)

5. Lithium

5.1. Off, but by how much?

The more significant Li measurements in halo stars since Spite and Spite (1982) are shown in Fig. 3, where $A(\text{Li}) = (\log(Li/H) + 12)$. At variance with the other elements there is a clear gap between the measured values and the WMAP

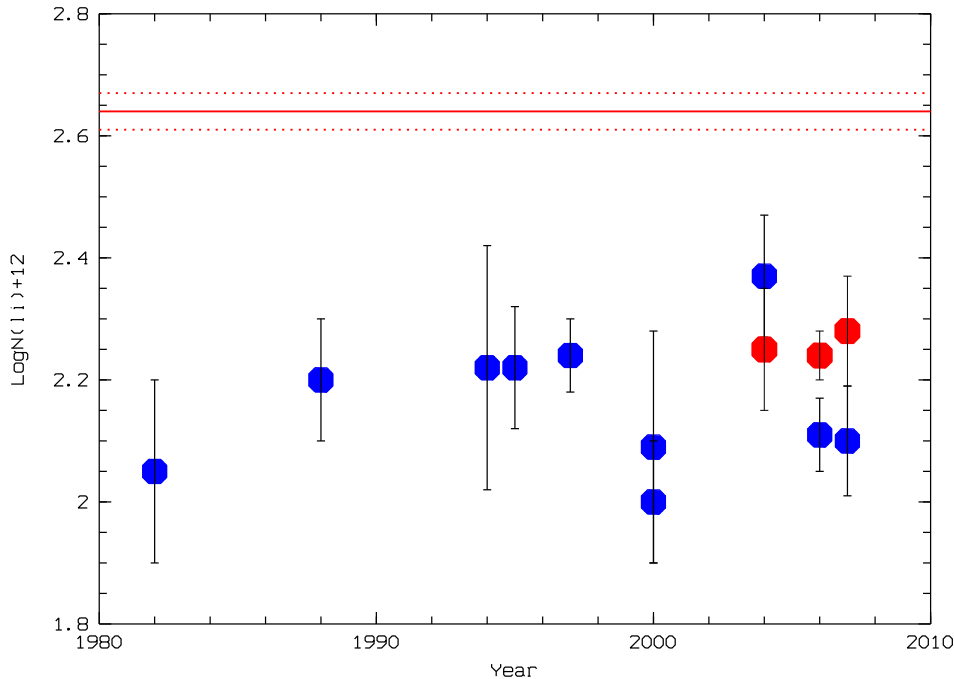


Figure 3. Filled blue circles are the historical record of primordial Li/H determinations in field halo stars since Spite and Spite (1982). The filled red circles are re-determinations after correction for some systematics as explained in the text. $A(\text{Li}) = (\log(Li/H) + 12)$

predictions, which seems to increase with time instead of converging onto the WMAP value. The most recent works are Asplund et al (2006), characterized by data with very high signal-to-noise, and Bonifacio et al (2007) who increases significantly the data points at low metallicity. Their results recomputed on common scales are shown in Fig 4 taken from Bonifacio et al (2007). Fig. 4 shows an increase in the dispersion at low metallicity, the presence of a slope with metallicity, or more precisely of a discontinuity in the Li abundance at $[\text{Fe}/\text{H}] \approx -2.5$ and even a possible drop out of Li abundance at about $[\text{Fe}/\text{H}] = -3.5$. Both works conclude for a rather low Li primordial value somewhat around $A(\text{Li}) = 2.1$, or even 2.0 if the observed slope is extrapolated at metallicities of $\text{Fe}/\text{H} = -3.5$. Thus, we note that the most recent values are very close to the initial value of 2.05 proposed by the Spites more than 20 years ago.

Li is mostly ionized and remains very sensitive to the T_{eff} . At temperatures of interest an error of 100 K in T_{eff} translates into about 0.08 dex in Li abundance. Both Asplund et al (2006) and Bonifacio et al (2007) use T_{eff} obtained through $\text{H}\alpha$ fitting and adopting the Barklem et al (2000, 2002) theory of collisional broadening. This new treatment provides lower Li values by ≈ 0.1 dex at lower metallicities with comparison to the Ali Griem (1966) theory generally adopted in the preceding works. Thus, these T_{eff} are likely responsible of the abrupt change in the Li abundances observed at $[\text{Fe}/\text{H}] \approx -2.5$, and of the low values obtained at lower metallicities. For instance, keeping only the

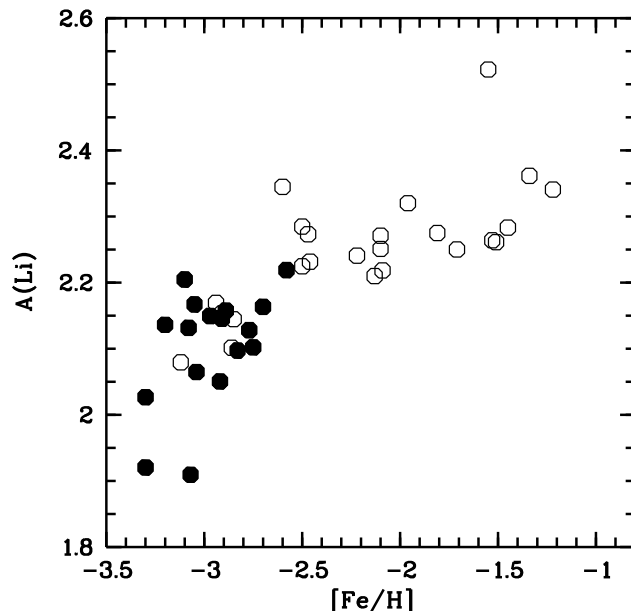


Figure 4. Li/H from Asplund et al (2006) (circles) and Bonifacio et al (2007) (filled circles) plotted on a common scale, from Bonifacio et al (2007)

sample of 19 stars with metallicity $[\text{Fe}/\text{H}] > -2.5$ from Asplund et al (2006) we obtain $A(\text{Li}) = 2.24 \pm 0.04$. Moreover, the data of Bonifacio et al (2007) but with different T_{eff} obtained by using the Ali-Griem (1966) theory provide the value of $A(\text{Li}) = 2.28 \pm 0.09$, significantly enhancing by ≈ 0.2 dex the average value (Bonifacio et al 2003).

As pointed out in Molaro et al (1995) the adoption of T_{eff} obtained with the Infra-Red-Flux-Method is levelling out any slope of Li with metallicity. This has been also confirmed by Bonifacio and Molaro (1997) and Melendez and Ramirez (2004) which make use of the IRFM T_{eff} and, while sharing several stars in common with Asplund et al (2006), do not find any evidence of Li slope with metallicity. Fig. 5 of Asplund et al compares the T_{eff} obtained from $\text{H}\alpha$ fitting plus Barklem theory for collisional broadening with those obtained with IRFM method and reveal a divergence between the two scales at low metallicities, i.e. $[\text{Fe}/\text{H}] < -2.5$. The IRFM method faces problems with reddening correction and with the difficulty of having accurate K magnitudes, but is less model dependent, and therefore less sensitive to our ability of modeling the stellar atmosphere. Moreover, Barklem (2007) points out that NLTE effects could be important in the wings of the balmer lines thus questioning the T_{eff} obtained in this way.

Melendez and Ramirez (2004) by means of IRFM value obtained $A(\text{Li}) = 2.37 \pm 0.06$. However, this value cannot be taken at face value since it is obtained by means of stellar atmospheric models which provide systematically higher Li abundance than other codes. They use the Kurucz models which adopt an

approximate treatment for overshooting which has been shown to provide an unsatisfactory color match at low metallicity and should not be used (Castelli et al 1997). Considering this effect their value should be lowered by about 0.08 dex, plus an additional correction for the NLTE correction not taken into account, to reach a final value of ≈ 2.25 .

Thus, eliminating the data values obtained with T_{eff} from Barklem theory at low metallicities, which is likely affected by some systematics, it is possible to find a convergence of the various measures and methods around a common range of values between $A(Li) = 2.24$ - 2.28 . This still remains significantly below the WMAP predicted value, but not as much as the factor 4 implied by the Asplund et al (2006) and Bonifacio et al (2007) measures.

The hypothetical presence of a drop in Li at very low metallicities may find support also in the absence of Li in HE 1327-2326 a dwarf with $[Fe/H] = -5.45$ (Aoki et al 2006). However, HE 1327-232 is rather chemically peculiar with $[C/Fe] = +4$ and the chemical composition may reflect single supernovae contamination were most of the Li is burned out. On the other hand the more "normal" metal poor dwarf CS 22876-32 with $[Fe/H] = -3.7$ shows $A(Li) = 2.2$ in the main component of the binary system suggesting a normal behaviour of Li at very low metallicities (Gonzalez-Hernandez et al 2007).

5.2. Is the Li puzzle solved?

Stellar depletion either by rotationally induced mixing or diffusion have been suggested as possible mechanisms able to reduce the Li abundance in halo stars. These models predict more dispersion in the Li abundances of what is observed in the halo stars and a pronounced down turn in the Li abundances at the hot end of the Li plateau. Richard et al (2005) invoke some extra turbulence to limit the diffusion in the hotter stars and to restore uniform Li abundance along all the plateau. Recently, Korn et al (2006) claimed the detection of a diffusion "signature" in the Globular Cluster NGC 6397. According to their analysis the Turn Off stars in this cluster exhibit lower iron and lithium abundances than the slightly more evolved stars. These observations may be interpreted in the framework of the diffusive models of Richard et al (2005) and this has been regarded as the solution of the Li problem (Charbonnel 2006).

The Korn et al result is very suggestive; however, it again relies heavily on the adopted temperature scale and an increase by only 100 K of the effective temperature assigned to the TO stars would remove the abundance differences between these and subgiant stars. Previous analyses of the same cluster by Castilho et al (2000) and Gratton et al (2001), with different assumptions on the effective temperature scale, failed to find any difference in $[Fe/H]$ between TO, subgiant, and giant stars. Bonifacio et al (2002) studying the Li in the this cluster obtained a slightly hotter temperature for the TO and $A(Li) = 2.34$ which suffices to eliminate any Li difference between the TO and subgiants. At deep inspection globular clusters show Li scatter among the mean sequence stars which cannot be related to diffusive processes since they show Li-O and Li-Na anticorrelations. These have been observed in NGC 6752 (Pasquini et al 2005) and 47 Tuc (Bonifacio et al 2007) and suggest that the formation of globular clusters could be a complex process where it may be difficult to disentangle small diffusive signatures.

The diffusion hypothesis encounters an additional problem with the ${}^6\text{Li}$ detection in some halo stars by Asplund et al. (2006). In the presence of diffusion of the sort required to reproduce the ${}^7\text{Li}$ expected for WMAP, ${}^6\text{Li}$ is depleted by the same processes in an even larger amount. When pre-main sequence destruction is also considered the resulting ${}^6\text{Li}$ original value is almost comparable to the ${}^7\text{Li}$ level. As noted by Asplund et al (2006) the Richard et al (2005) model T6.25 when applied to the star LP 815-43 implies an unplausible high original ${}^6\text{Li}$ of ≈ 2.6 . This level of ${}^6\text{Li}$ would pose serious problems for the ${}^6\text{Li}$ synthesis, so that the presence of the Li isotope challenges the diffusion hypothesis (cfr Prantzos 2007)

The reason for the disagreement of the observations with the WMAP value is not readily identified. Atmospheric modeling problems are unlikely but not completely ruled out. Observations of the Li subordinate, which forms in a different layer in the atmosphere, provide consistent results to that of the main Li line (Bonifacio and Molaro 1998, Asplund et al 2006). First results from 3D atmospheric models show very small departures from 1D NLTE Li abundances with small but negative corrections thus eventually exacerbating the disagreement with the WMAP based prediction (Asplund et al 2003, Barklem et al 2003).

A nuclear fix to the Li problem is also unlikely (Cyburt et al 2004). Coc et al (2004) suggested that the cross section of ${}^7\text{Be}(d, p){}^2\text{He}$ and ${}^7\text{Be}(d, \alpha){}^5\text{Li}$ could be larger, but recent measures of this cross section at energies appropriate to the big bang environment found it 10 *smaller*, than leaving not much room for a Li change due to nuclear cross sections (Angulo et al 2005).

Piau et al (2006) suggested that significant matter processing in pregalactic PopIII stars could lower the Li abundance and also explain the presence of Li dispersion among the metal poor sample as well as the fact the absence of Li in HE 1327-2326. However, as pointed out by Prantzos (2007) the considerable amount of matter recycling in PopIII stars should produce significant amounts of heavy elements, which are not seen.

Although a solution of the Li problem may still reside in our ability to reconstruct the complexity of the stellar atmosphere, systematic errors in the T_{eff} or 3D effects able to increase the Li value to match the WMAP value seem unlikely. It is thus possible that the disagreement may be real revealing the presence of unaccounted processes in the BBN. Neutral decaying particles (Jedamzik 2006, but see Ellis et al 2005) or a variation of the deuteron binding energy (Dent et al 2007) have been already considered and are among the more intriguing scenarios for the solution of the puzzle.

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